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ORIGINAL ARTICLE

Behavior of repeatedly loaded rectangular footings resting on reinforced sand

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KEYWORDS

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Abstract The paper presents a laboratory study of the effect of geosynthetic reinforcement on the cumulative settlement of repeatedly loaded rectangular model footings placed on reinforced sand. Repeated load tests were carried out with different initial monotonic load levels to simulate structures in which live loads change slowly and repeatedly such as petroleum tanks and ship repair tracks. Three series of tests were carried out. Tests of series 1 were performed to determine the ultimate monotonic bearing capacity. Tests of series 2 were performed on unreinforced sand under vertical repeated loads. Tests of series 3 were performed to study the effect of sand reinforcement on the footing response under the same loads. The studied parameters include the initial monotonic load levels, the number of load cycles, and the relative density of sand along with geosynthetic parameters including size and number of layers. Both the ultimate bearing load and the cumulative settlement were obtained and analyzed.
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1. Introduction

Shallow foundations such as rectangular footings are widely used in transmitting loads from the superstructure to the supporting soils. After the foundation is constructed, the soil is permanently loaded by both the gravity loads and the live loads of the superstructure. In most constructions such as residential buildings, the live loads are much less than the gravity loads (own wt. of structure). However, in some structures, the live loads are greater than the dead loads of the structure itself and change with time, such as the loads of petroleum tanks and ship repair tracks. In petroleum tanks, petrol was transferred and stored in the tanks until it was carried to petroleum stations. Therefore, the supporting soil is subjected to repeated load whose frequency and load amplitude are dependent on the rate of filling and emptying the tanks. Also in the ship

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repair tracks, the ship loads are transferred to the footings during the ship repair and the load is removed totally by moving the ship to the sea. Several studies have been carried out to understand the behavior of model footings on sand deposits and subjected to cyclic loads. Raymond and Comos [1] studied the behavior of model strip surface footing under vertical cyclic load and reported that the permanent settlement increased as both the number of load cycles and the magnitude of cyclic load increased. Poulos et al. [2] carried out a series of model footing tests on sands with different relative densities under cyclic vertical loading conditions. Sawicki et al. [3] reported test results of strip and circular model footing supported on dry fine to medium sand and subjected to cyclic vertical load, the magnitude of which was equal to some fraction of the foundation bearing capacity.

Several studies have reported the successful use of soil reinforcement as a cost-effective method to increase the ultimate bearing capacity and to decrease the settlement values under shallow footings to accepted limits [4–8]. This was achieved by the inclusion of multiple layers of geogrid at different depths and widths under the footings. This reinforcement consists of a series of interlocking cells which contain and confine the soil within its pockets creating an interlocking action between the sand and the grid. This interlock enables the geogrid to resist the horizontal shear stresses built up in the soil mass under the footing and to transfer them to the adjacent stable layers of soils and thereby improve the vertical behavior of the footing. However, few studies have focused on the behavior of shallow footing subjected to cyclic loading and resting on reinforced sand. Yeo et al. [9] and Das et al. [10] studied the ultimate bearing capacity and the settlement of square and strip model footings supported on geogrid reinforced sand and subjected to the sum of static load and vertical cyclic load of different intensities. Raymond [11] studied the effect of geosynthetic reinforcement on the settlement of a plane strain footing supported on a thin layer of granular aggregate overlying different compressible bases and subjected to repeated load which returned to zero at the end of each cycle to simulate a vehicle loading on a track support. Shin et al. [12] reported laboratory model tests results of the permanent settlement of the subbase layer reinforced with geogrid layers due to cyclic load of the railroad.

Most of the previous studies deal with the behavior of reinforced sands under cyclic vertical loads simulating either train and vehicle loads or sum of static loads and cyclic loads of high frequencies. To the best knowledge of the authors, the settlement of reinforced sand bed subjected to slowly repeated load simulating a loading condition such as the case of petrol tanks has not yet been investigated. Hence, many questions still remain such as the effect of such repeated loads on both the

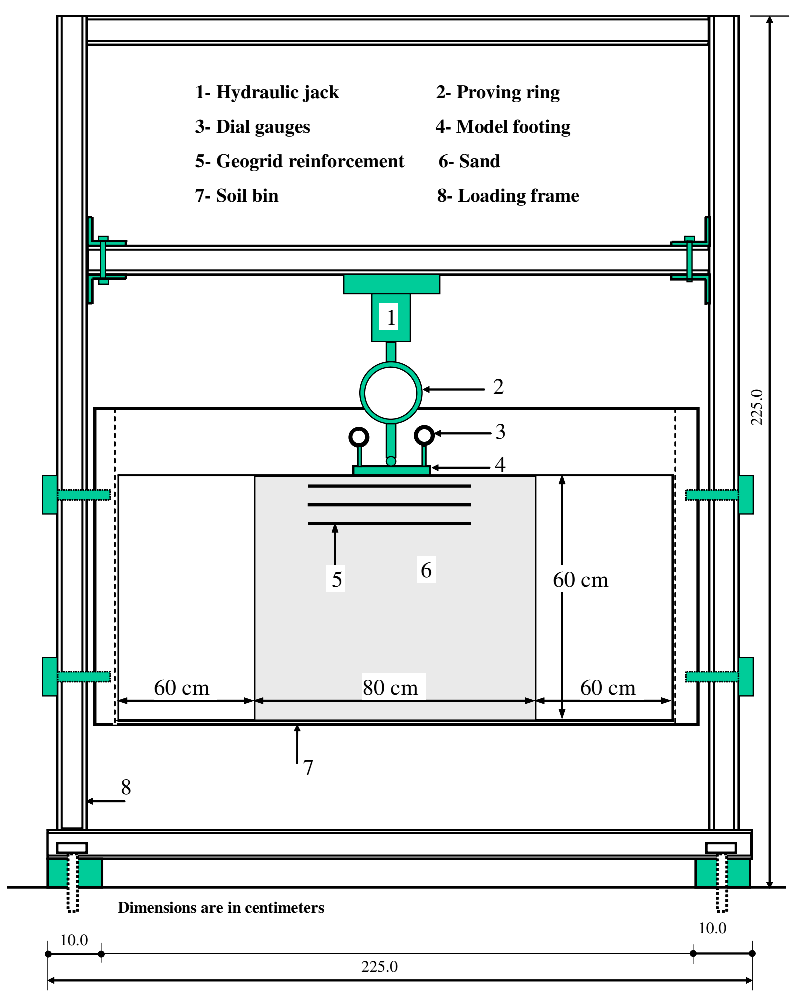

Figure 1 Overall view of the experimental apparatus.

performance of soil and the permanent cumulative settlement. Therefore, the aim of this research is to model and study the effect of soil reinforcement on footing response under repeated load. To achieve those objectives more than 34 tests were carried out on model footings under a wide range of parameters and sand relative densities.

2. Laboratory model tests

2.1. Soil bin and footing

The experimental apparatus consists of two main elements: the soil bin and the loading system. The soil bin, which has inside dimensions of 2.00 m × 0.60 m in plane and 0.60 m in depth was made from steel. The soil bin was supported directly on two steel columns. These columns were firmly fixed in two horizontal steel beams, which were firmly clamped in the laboratory ground using four pins. The soil bin was divided into three cells having lengths of 0.60, 0.80 and 0.60 m, respectively. The tests were performed in the middle cell. The soil bin was built sufficiently rigid. To ensure the rigidity of the bin, both the front and back walls of the bin were braced on their outer surface with two steel beams fitted horizontally at equal spacing. The inside walls of the bin were lined by fiber glass sheets to minimize side friction. The loading system was mounted by a horizontal SIB steel beam supported on the two columns. It consists of a hand-operated hydraulic jack and pre-calibrated load ring. Rectangular model footings were machined from steel with a notch at its top surface. The notch is at the center of the footing within ±1 mm accuracy. The footings were 80 mm in width, 120 mm in length and 16 mm in thickness. A rough base condition was achieved by fixing a thin layer of sand onto the base of the model footing with epoxy glue. The load is transferred to the footing through a ball bearing which was placed between the footing and the proving ring. Such an arrangement produced a hinge, which allowed the footing to rotate freely as the underlying soil approached failure and eliminated any potential moment transfer from the loading fixture. An overall view of the used apparatus is illustrated in Fig. 1.

2.2. Test materials

The sand used in this research is medium silica sand washed, dried and sorted by particle size. It is composed of rounded to sub-rounded particles. The specific gravity of the soil particles was measured according to ASTM standards 854. Three tests were carried out producing an average value of 2.66. The maximum and the minimum dry unit weights of the sand were found to be 18.44 and 15.21 kN/m^3 and the corresponding values of the minimum and the maximum void ratios were 0.44 and 0.75. The particle size distribution was determined using the dry sieving method and the results are shown in Fig. 2. The effective size (D_{10}), the mean particle size (D_{50}), the uniformity coefficient (C_u), and the coefficient of curvature (C_c) for the sand were 0.12 mm, 0.38 mm, 4.25 and 0.653, respectively. In order to achieve reasonably homogeneous sand beds of reproducible packing, controlled pouring and tamping techniques were used to deposit sand in layers into the soil bin. In this method the quantity of sand for each layer, which was required to produce a specific relative density, was first weighed to an accuracy of ±5 g and placed in the bin and specify tamped using manual compactor until achieving the required layer height. The experimental tests were conducted on samples prepared with average unit weights of 16.37 and 17.50 kN/m^3 representing loose and dense conditions, respectively. The relative densities of the samples were 40% and 75%, respectively. The estimated internal friction angle of the sand determined from direct shear tests using specimens prepared by dry tamping at the same relative densities were 33.2° and 39.4°, respectively.

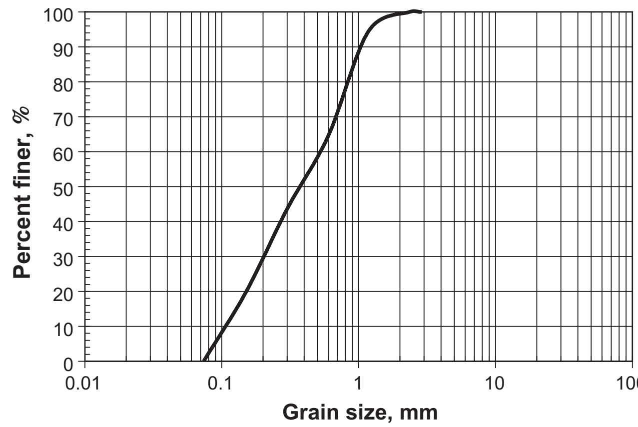

Figure 2 Grain size distribution of the used sand.

Table 1 Engineering properties of geogrid.

Structure	Mono-oriented geogrid
Aperture shape	Oval apertures
Aperture size (mm × mm)	(13/20) × 220
Weight (g/m^2)	300.00
Polymer type	HDPE
Tensile strength at 2% strain (kN/m)	11
Tensile strength at 5% strain (kN/m)	25
Peak tensile strength (kN/m)	45
Yield point elongation (%)	11.5
Long term design strength (N/m)	21.2

2.3. Geogrid reinforcement

Tenax TT Samp with peak tensile strength of 45 kN/m was used as reinforcing material for the model tests. These geogrids were manufactured by extruding and mono-directional drawing of High Density Polyethylene (HDPE) grids. Typical physical and technical properties of the grids were obtained from the manufacturer's data sheet and are given in Table 1.

2.4. The experimental setup and test program

An extensive test program was carried out to study the settlement behavior of rectangular model footings supported on reinforced sand under the effect of repeated load. Sand samples with a height of 500 mm were constructed in 50 mm layers. The inner faces of the bin were marked at 50 mm intervals to facilitate the accurate preparation of the sand bed in layers. On reaching the reinforcement level, a geogrid

Table 2 Model tests program.

Series	Constant parameters	Variable parameters
1	Monotonic, unreinforced sand	R_d = 40% and 75%
2	Monotonic, reinforced sand, $N = 3$, $b/B = 5.0$	R_d = 40% and 75%
3	Monotonic, reinforced sand, R_d = 40%, $b/B = 5.0$	N = 1, 2, 3 and 4
4	Monotonic, reinforced sand, R_d = 75%, $b/B = 5.0$	N = 1, 2, 3 and 4
5	Monotonic, reinforced sand, R_d = 40%, $N = 3$	b/B = 2.0, 3.0, 4.0, 5.0 and 6.0
6	Monotonic, reinforced sand, R_d = 75%, $N = 3$	b/B = 2.0, 3.0, 4.0, 5.0 and 6.0
7	Repeated, unreinforced sand, R_d = 75%	q_o/q_u = 20%, 40%, 70% and 85%
8	Repeated, unreinforced sand, R_d = 40%	q_o/q_u = 20%, 40%, 70% and 85%
9	Repeated, reinforced sand, R_d = 75%, $N = 3$, $b/B = 5.0$	q_o/q_u = 20%, 40%, 70% and 85%
10	Repeated, reinforced sand, R_d = 40%, $N = 3$, $b/B = 5.0$	q_o/q_u = 20%, 40%, 70% and 85%

Note: See Fig. 3 for definition of the variable. Footing width (B) = 80 mm, footing length (L) = 120 mm, the depth of top layer (u/B) = 0.30, the vertical spacing between layers (x/B) = 0.60 and q_c/q_o = 100% are always constant.

layer was placed and the next layer of sand was poured and tamped. The relative density achieved during the tests and the uniformity of the sand samples were monitored by collecting the samples in small cans of known volume placed at different locations in the soil bin. Each mould was carefully excavated and the density of the sample was calculated. One to four geogrid layers 600 mm in length (parallel to footing length) and different widths were used to reinforce sand bed. The preparation of the sand bed above the reinforcement was continued in tamped layers up to the required level and the footing was placed on position. All tests were conducted with new sheets of geogrid. Great care was given to level the top surface using special rulers so that the relative density of the top surface was not affected. Finally the load was applied by manual hydraulic jack in small increments until reaching the required initial monotonic load value. Each load increment was maintained at constant value until the dial gauges readings of footing displacements had stabilized. When the stage of repeated load started, the load varied between a maximum value and a minimum value of zero at the end of the cycle. The value of maximum load was equal to the initial applied monotonic load on the footing. The model footing displacements were measured using two 50 mm travel dial gauge accurate to 0.001 mm placed on opposite sides of the footing as shown in Fig. 1.

Previous work results of model footing on reinforced sand under monotonic loading [4–8,12] have shown that the values of u/B (u is the depth of top geogrid layer) and the vertical spacing between geogrid layers (x) that provide the maximum improvement in bearing capacity of strip and square footings supported on medium dense to dense sand may vary between 0.25 and 0.50 for u/B and between 0.50 and 0.70 for x/B. Therefore, the values of $u/B = 0.30$ and $x/B = 0.60$ were kept constant in the entire test program. Ten series of tests in three main groups were performed on model footings supported on sand beds of different sand densities. In the first group series 1 and 2 were performed to determine the ultimate monotonic bearing capacity of footing on both unreinforced and reinforced sand. Four series (3–6) were conducted to determine the optimum number of layers (N) and geogrid layer width (b) that give the maximum improvement in the footing behavior under monotonic load. Tests of group II (series 7 and 8) were performed on repeatedly loaded footing supported on unreinforced sand. The studied parameters were the relative density of sand (R_d), the initial monotonic load level (q_o/q_u) and the number of load cycles (N_c). Finally, group III (series 9 and 10) were carried out to study the response of repeatedly loaded footing supported on reinforced sand. The geometry of the soil, footing and geogrid layers is shown in Fig. 3. Table 2 summaries all the tests programs with both the constant and varied parameters illustrated. Several tests were repeated at least twice to verify the repeatability and the consistency of the test data.

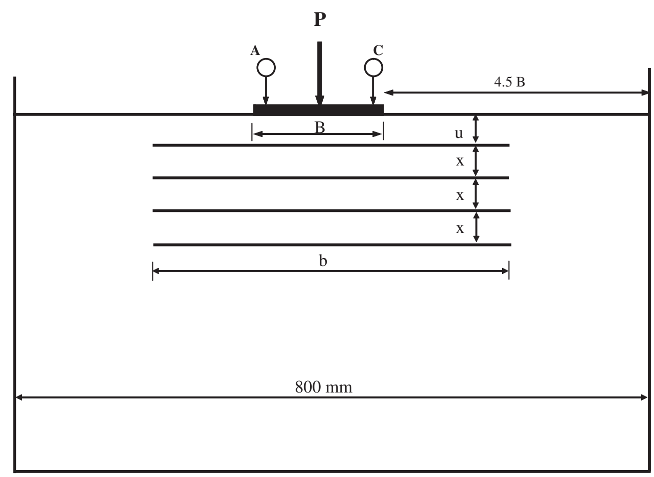

Figure 3 Model footing and geometric parameters.

3. Results and discussion

3.1. Monotonic load tests

Monotonic tests were carried out on both unreinforced and reinforced sand deposits not only to measure the ultimate bearing capacity of the footing to establish the maximum values of the cyclic loads and the initial load levels but also to determine the optimum number and size of soil reinforcement. The bearing capacity improvement of the footing on the reinforced sand is represented using bearing capacity ratio (BCR) which is the ratio of the footing ultimate pressure on reinforced soil ($q_{u\ reinforced}$) to the footing ultimate pressure in tests without reinforcement (q_u). The footing settlement (S) is expressed in non-dimensional form in terms of the footing width (B) as the ratio (S/B, %). The ultimate bearing capacities for the footing-soil systems are determined from the load–displacement curves as the pronounced peaks, after which the footing collapses and the load decreases. In curves, which did not exhibit a definite failure point, the ultimate load is taken as the point at which the slope of the load settlement curve first reaches zero or a steady minimum value [13]. The measured ultimate bearing loads for the model footing on unreinforced loose and dense sands were 538 N and 805 N, respectively. The measured ultimate bearing loads for the model footing on reinforced loose and dense sands using three layers of geogrid with $b/B = 5$ were 778 N and 1400 N, respectively.

Typical variations of bearing pressure with footing settlement ratios (S/B) for reinforced sand beds for different number of geogrid layers are presented in Fig. 4. It can be seen that the inclusion of geogrid layers appreciably improves the bearing capacity of the footing as well as the stiffness of the foundation bed. Comparing the curves of unreinforced and reinforced sand for the same bearing pressure, it can be seen that soil reinforcement much decreases the settlement ratio. Therefore, it can be concluded that in cases where structures are very sensitive to settlement, soil reinforcement can be used to obtain the same allowable bearing capacity at a much lower settlement with the same sand density. This decrease in vertical settlement due to the inclusion of the geogrid layers can be attributed to the reinforcement mechanism, which limits the spreading and lateral deformations of sand particles. With increasing the number of geogrid layers, the contact area and the interlocking between geogrid layers and soil increase. Consequently, larger soil displacements and horizontal shear stresses built up in the soil under the footing were resisted and transferred by geogrid layers to larger mass of soil. Therefore, the failure wedge becomes larger and the frictional resistance on failure planes becomes greater.

3.1.1. Effect of number of geogrid layers

Eight tests (series 3 and 4) were performed to study the effect of the number of geogrid layers on the behavior of the monotonically loaded footing supported on loose and dense sands. In the two series only the number of layers was varied while the other parameters including (u/B), (x/B) and (b/B) were kept constant equal to 0.30, 0.60 and 5.0, respectively. Fig. 5 presents variations of BCR against the number of layers for the different sand densities. The inclusion of geogrid layers has a much better effect when it was placed in dense sand than in loose sand. The figure clearly indicates that the BCR much improves with the number of geogrid layers for both sand densities. However, the rate of increase in BCR decreases with the increasing number of geogrid layers until $N = 3$ after which the rate of load improvement becomes much less. A similar conclusion that $N = 3$ is the optimum number of layers was given by previous studies of strip or square footings over reinforced sands [6–8]. However, it should be mentioned that the optimum number of geogrid layers is much dependent on the vertical spacing between geogrid layers and the embedment depth of the first layer. This is due to the fact that soil reinforcement would be significant when placed in the effective zone under the footing.

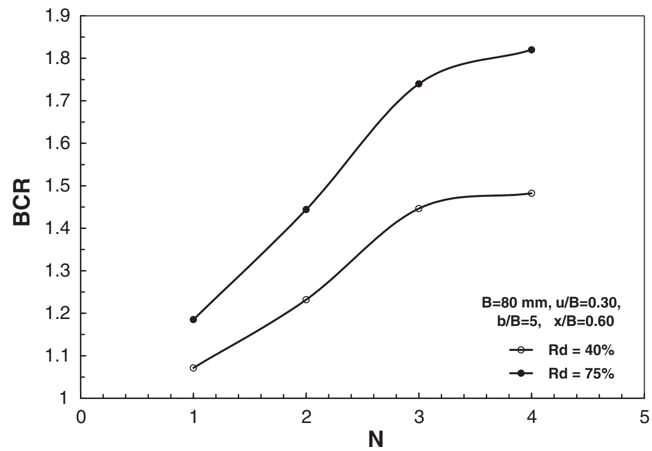

Figure 5 Variations of BCR with N.

3.1.2. Effect of geogrid layer width

Ten model tests in two series (5 and 6) using three layers of geogrid were performed to study the effect of the layer width on the behavior of rectangular footing. All the variable parameters were kept constant with varying only the layer width for both loose and dense sands. Fig. 6 shows the variation of BCR against the b/B ratio for footings supported on different sand densities. It is clear that the BCR increases with increasing

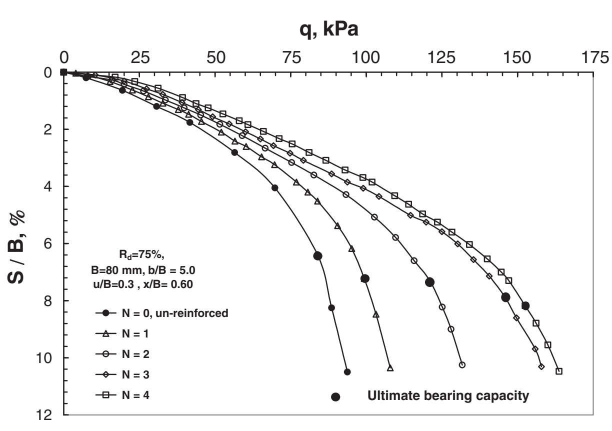

Figure 4 Variation of (q) with (S/B) for different number of layers.

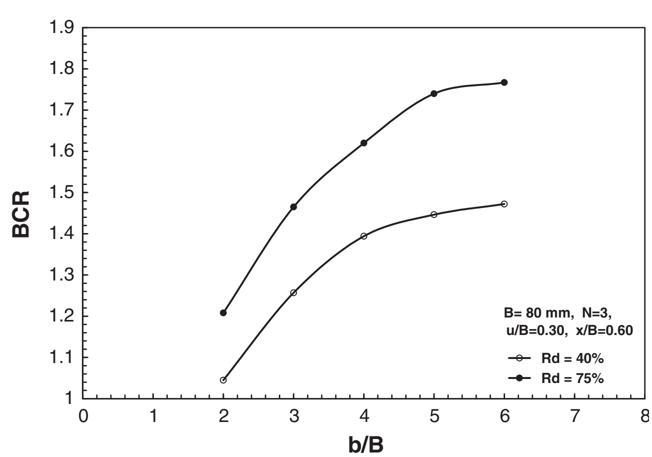

Figure 6 Variations of BCR with b/B.

geogrid layer width. A greater effect of soil reinforcement when placed in dense sand than that when located in loose sand can be observed. However, this improvement in the ultimate bearing capacity with increasing layer width is significant until a value of (L/B = 5) beyond which further increase in layer width of geogrid does not show significant contribution in increasing the ultimate load of the footing. Therefore, on conducting repeated load tests it was decided to use three layers of geogrid each of which was five times the footing width (b/B = 5.0).

3.2. Repeated load tests

Upon determining the ultimate monotonic bearing capacity of the model footings on unreinforced and reinforced sands, repeated load tests were carried out. In these tests, initial monotonic load level equal to some fraction of the foundation bearing capacity was applied and then the footing was subjected to subsequent cycles of unloading and reloading. The footing settlement due to repeated load only is referred to as (S_c) and is expressed in non-dimensional form in terms of the footing width (B) as the ratio (S_c/B, %). Fig. 7 shows the variation of bearing load with (S/B) for initial monotonic pressure level (q_o/q_u) equal to 70% and the first 10 cycles of repeated load for model footing supported on unreinforced and reinforced dense sand. Initially, the load was increased monotonically from zero until it reached its specified maximum value (loading stage), at which point the load was decreased to zero value (unloading stage). Then, the load was applied and removed continuously (repeated load stage). The maximum applied load in this stage was equal the maximum load applied on the footing monotonically. The figure clearly shows that as the vertical stress increases monotonically the vertical settlement increases rapidly and upon decreasing the load there is some recoverable settlement (elastic rebound). As the first cycle of load was applied, the vertical settlement increased and slightly exceeded the previous maximum value. On unloading, the settlement did not return to its previous value and some plastic settlement remained. The settlement that occurred to the footing in the stage of repeated load was termed cumulative cyclic settlement. The permanent cumulative settlement increased with the number of load cycles and most of the settlement occurred due to the first few cycles. The cumulative settlement of both unreinforced and reinforced tests was obtained and discussed in the following sections.

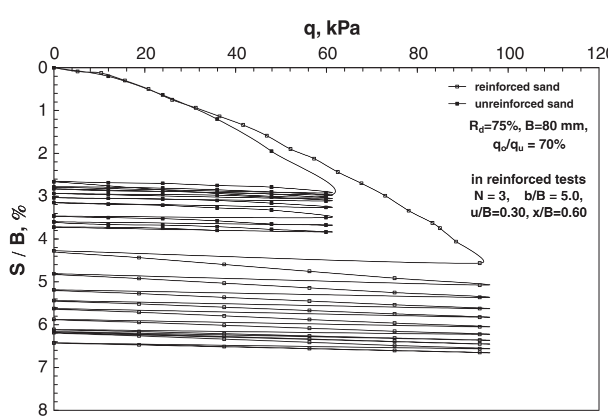

Figure 7 Variation of (q) with (S/B) for initial monotonic load and 10 cycles.

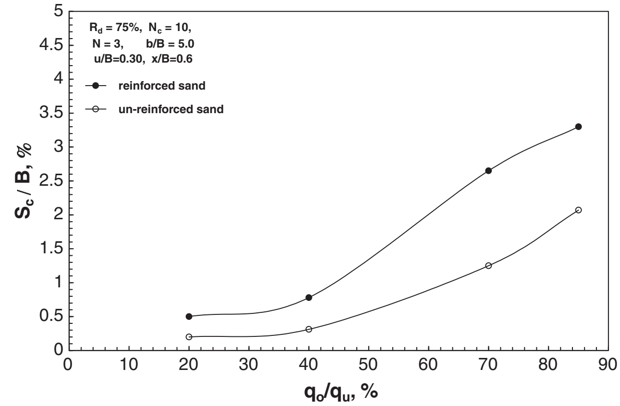

Figure 8 Variation of (q_o/q_u) with (S_c/B).

3.2.1. Effect of initial monotonic load level

In order to investigate the effect of initial monotonic load level (q_o/q_u) on the footing behavior, four series (7–10) were carried out using four different values of q_o/q_u = 20%, 40%, 70%, and 85%. While series 7 and 8 were carried out on unreinforced loose and dense sands, series 9 and 10 were performed on reinforced sands at the same densities. Three layers of geogrid with (b/B = 5.0) were used. Fig. 8 shows the variation of (q_o/q_u) with normalized cumulative cyclic settlement (S_c/B) for both unreinforced and reinforced dense sand after the application of 10 load cycles. The figure clearly shows that the cumulative settlement increases with increasing monotonic load level. Greater values for (S_c/B) for q_o/q_u of 70% and 85% can be observed relative to the value of (S_c/B) for q_o/q_u of 20% and 40%. Also, it can be seen that for the same initial monotonic load level the cyclic settlement for the reinforced settlement is greater than that of the unreinforced tests. This can be referred to the fact that both the series of repeated load tests on either reinforced or unreinforced sands were performed at the same normalized ratios q_o/q_u and q_o/q_u. As the ultimate bearing loads for reinforced tests are much greater than those of unreinforced sands, both the initial monotonic load and the cyclic load level are greater than those values in unreinforced tests.

3.2.2. Effect of number of load cycles

Fig. 9 shows the variation of both monotonic and cyclic settlements versus the number of cycles for rectangular footing supported on both unreinforced and reinforced dense sands. The

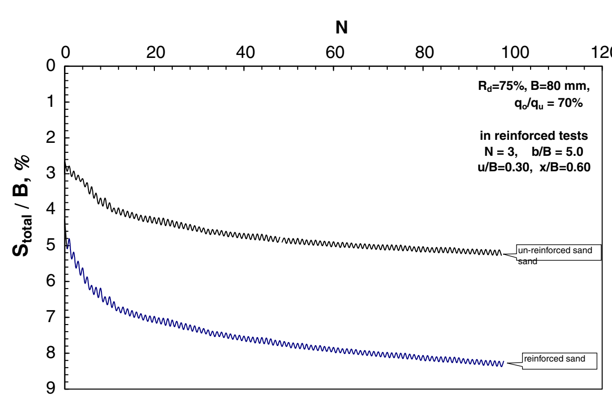

Figure 9 Variation of (N) with (S/B).

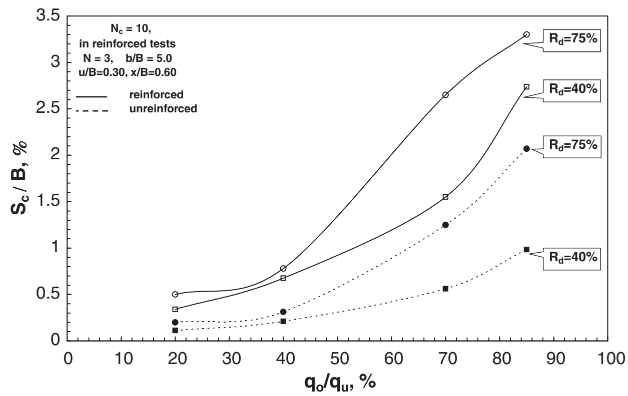

Figure 10 Variation of (q_o/q_u) with (S/B) for different relative densities.

initial monotonic load level q_o/q_u was 70% in the two tests. In the reinforced test three layers of geogrid with the ratio $(b/B = 5.0)$ were used. From the figures it can be seen that the cumulative cyclic settlement increases with gradually decreasing rate with the increase of the number of cycles. Greater effect can be seen with reinforced tests rather than unreinforced tests. The rate of settlement increase is very rapid for the first 10 cycles after which the rate becomes slower until the number of cycles of 70 cycles and then it decreases and tends to become constant. Although the rate of increase in settlement gradually decreases, there is no sign of stability after the application of 100 load cycles.

3.2.3. Effect of the soil relative density

In order to study the effect of relative density, four series of tests (7–10) were conducted on model footing supported on unreinforced and reinforced sand beds set up at two unit weights representing loose and dense relative densities. Fig. 10 compares the magnitudes of cumulative cyclic settlements after the application of 10 cycles ($N_c = 10$) for the two relative densities for different initial monotonic load levels of loads. The figure clearly shows that cyclic settlement increases with the initial monotonic load level for both relative densities. Also, for the same monotonic load level, the cyclic settlements in dense sands are greater than those in unreinforced sands (see explanation in the section 'Effect of initial monotonic load level'). Also the figure indicated that the sand density has a significant effect on the settlement in the unreinforced sand than that in the reinforced sand.

4. Scale effects

It is well known that due to scale effects and the nature of soils, soils may not play the same role in the laboratory models as in the prototype. These differences occur primarily because of the differences in stress level between the model tests and the field tests [13]. The stress level under the small scale model footing is much smaller than that under full scale foundation. This low stress in granular soils corresponds to a greater angle of internal friction when compared to the angle of friction at higher stress level. Therefore, the average shear strength mobilized along a slip line under the footing decreases with an increase of footing size due to the decrease in the angle of internal friction. Despite the mentioned disadvantages that scaling effects due to variations in stress level will occur in model tests and the tests results are of limited use in predicting the behavior of a particular prototype, the study indicated the benefits that can be obtained when using geogrid layers to reinforce sandy granular soils and provided a useful basis for further research using full-scale tests or centrifugal model tests and numerical studies leading to an increased understanding of the real behavior of soil reinforcement.

5. Conclusions

The behavior of repeatedly loaded model footings supported on both unreinforced and reinforced sands was studied. Repeated load tests were carried out with different initial monotonic load levels to simulate structures in which live loads change slowly and repeatedly from a maximum value to zero load at the end of load cycle. Reinforcement parameters including the size and number of layers along with the effect of the initial monotonic load levels, the number of load cycles, and the relative density of sand were examined. Based on the experimental test results the following conclusions can be drawn:

(1) In cases where structures are very sensitive to settlement, soil reinforcement can be used to obtain the same allowable bearing capacity at a much lower settlement with the same sand density.
(2) For the best improvement in a footing behavior resting on reinforced sand, an adequate size for each geogrid layer should be provided and an optimum number of geogrid layers should be used. The length should be greater than or equal to five times the footing width $(b/B = 5)$ and the recommended number of geogrid layers is 3.
(3) For the same number of load cycles, the cyclic load-induced settlement increases with increasing initial monotonic load.
(4) For a given initial monotonic load ratio (q_o/q_u) and the number of load cycles, the magnitude of cumulative settlement due to vertical cyclic loading increases with the increase of sand relative density due to the increase of the footing monotonic bearing load and hence the values of both initial monotonic load and cyclic load.
(5) For the same initial monotonic load and sand relative density, the permanent cyclic settlement increased with the number of cycles.
(6) The cumulative settlement increased with the number of load cycles with a gradually decreasing rate. Most of the settlement occurred due to the first few cycles after which the rate becomes slower until the number of cycles of 70 cycles and then it decreases and tends to become constant.

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